Working Group 2 Report: Accelerators for Neutrinos

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Intro

The Accelerators for Neutrino working group addressed the following points:

- The proton (or other) beam requirements to meet the above needs.
- The capability of existing or planned accelerator facilities to satisfy the above requirements, and If not: the necessary upgrades or new facilities.
- Enabling R&D and test facilities necessary to develop upgrades and new facilities.

The proton beam requirements are derived from the neutrino physics input, and these are provided largely by the Artificial Neutrino Sources working group of the Neutrino Physics frontier. The existing neutrino beam capabilities (and proton driver beam characteristics) are summarized in Table 1. Table 2 shows planned upgrades or new artificial neutrino beam capabilities. Add words about what accelerator R&D is needed to meet needs.

Separately the worldwide high power proton beam existing capabilities were assessed, and are summarized in Table 3. Table 4 lists the planned upgrades and ongoing projects for high power proton accelerators. Since the last Snowmass exercise, a number of facilities world-wide now routinely operate at or near the MW level (PSI, SNS, J-PARC, FNAL MI). Furthermore, a number of upgrade projects will soon be online providing > 1MW capability (e.g. the PIP-II, ESS, J-PARC, SNS upgrade).

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		Secondary beam					Primary beam				
Project	Primary Physics Goal	Particle	Purity	Energy [GeV]	Spatial characteristics	Timing	Particle	Energy [GeV]	Power [MW]	Timing	References
NuMI/NovA Upgrade	LBLO	,		2	Pulsed-horn forward beam	?	p	120	>0.9	?	NF145
T2K Upgrade	LBLO	,		2	Pulsed-horn forward beam	?	p	30	1.3	?	NF187
LBNF/DUNE	LBLO	,		0.5-4	Pulsed-horn forward beam	Low Duty factor	p	30-120	1.2	Low duty factor	DUNE TDR
LBNF/DUNE Upgrade	CP violation	,		0.5-4	Pulsed-horn forward beam	Low Duty factor	p	30-120	>2.4	Low duty factor	AF092, DUNE TDR

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LBNF/DUNE Timing Upgrade	CP violation	’		0.5-4	Pulsed-horn forward	Low Duty factor	p	120	1.2	<200 ps bunches	NF116
LBNF/DUNE Low Energy Upgrade	CP violation, solar oscillation parameters	’		0-4	Pulsed-horn forward beam	Dual BNB/MI timing	p	30 and 120	?	Dual BNB/MI timing	AF092, DUNE TDR
LBNF/DUNE HE Upgrade	nu_tau appearance : unitarity, NSI			0.5-10	Pulsed-horn forward beam	Low Duty factor	p	120	>1.2	Low Duty factor	AF092, DUNE TDR
FASER2 /FASER	BSM, interaction, Dark matter	’ ’ ,			Secondary beams emerging from collider IP	Continuous - 25 ns structure	p	7000	-	Continuous - 25 ns structure	EF038
ORNL SNS	BSM, interactions, steriles, Dark Matter	’ ’	99% (https://arxiv.org/abs/2109.11049)	0-0.052	High-purity pion decay at rest	~400 ns width for prompt pidk, 2.2 us for mudk	p	1-1.3	1.4 (First TS) then 2.0;eventually 1.8	400 ns @ 60 Hz	NF108, NF095, NF111, NF067, NF161

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						@ 60Hz			FTS+0.6 STS		
LANL SNS	?	?		?	?	?	?	?	?	?	AF215
JPARC SNS	Sterile search, BSM, interaction	, ,		0-53 MeV, 236 MeV	Beam dump	2 100 ns pulses separated by 500 ns, @ 25 Hz. But, note muon lifetime of 2 us.	p	3	Currently 750. Planned: 1000.	2 100 ns pulses separated by 500 ns, @ 25 Hz	NF128

Table 1: Existing neutrino beams or under construction/upgrade. For the latter requirements are presented. BSM=Beyond the Standard Model, LBLO=Long Baseline Oscillations, BNB=(FNAL) Booster Neutrino Beam, MI=(FNAL) Main Injector, LE=Low Energy, HE=High Energy, NSI=Non-Standard Neutrino Interactions. Table from Neutrino Frontier (L. Fields).

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		Secondary beam					Primary beam				
Project	Primary Physics Goal	Particle	Purity	Energy [GeV]	Spatial characteristics	Timing	Particle	Energy [GeV]	Power [MW]	Timing	References
PIP2-BD(PIP-II Beam Dump Experiment)	Dark matter and Sterile search	, , BSM		O(0.01-1)	Beam dump	Low duty factor	p	O(1)	0.1-1	Low duty factor	AF092, AF185, RF099, https://arxiv.org/abs/2106.02133
SBN-BD (SBN Beam Dump Experiment)	Dark matter and Sterile search	, , BSM		O(0.01-0.1)	Beam dump	Low duty factor	p	8	0.1-1	Low duty factor	AF092 RF084 https://arxiv.org/abs/2106.02133
IsoDAR	Sterile search, BSM		100%	0.000-0.015	Beam dump	Continuous	p	0.06	0.6	None; continuous wave	AF092 RF084
ESSnuSB	CP violation			2-2.5	Pulsed Horn Forward	14 Hz	p (H-)	2.5	5	1.4 μs duration	NF062

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					Beam						
ESSnuSB-LEnuSTORM	cross sections, steriles		50%/50%	0.4		14 Hz	p (H-)	2.5	5	1.4 μs duration	NF062
TeV Muon collider	BSM, energy frontier discoveries	$\mu^+\mu^-$	n/a	0.2 GeV	high efficiency collection system	5-15 Hz	p(H-)	4-8 GeV	2-4 MW	one (several) 1-2 ns bunches (1 to 12)	AF081
NuStorm	Sterile search	, , ,	Precise mix	1-4 GeV	Relativistic muon decay		p	100	156 kW	10 **μ**s every 3.6 s.	NF067 requires μ storage ring
Moment	?	?	?	?	?	?	?	?	?	?	?

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ENUBET	Precise measurement of nu cross sections, sterile nu using a beam with well known normalization	charged pions, kaons	K is ~5/10% of pions	4-9 GeV/c	after collimation and focusing O(10x10) cm2	O(1e10-11) pi+/K+ over a (2-4 s slow extraction) with quad focusing ora sequence of O(1) ms bursts with ~10 Hz (burst mode slow extraction)for horn focusing	protons	30-120-400 GeV	100 kW or more	O(1e13) POT over a (2-4 s slow extraction) with quad focusing or a sequence of O(1) ms bursts with ~10 Hz (burst mode slow extraction) for horn focusing	https://cds.cern.ch/record/2759849?ln=en

Table 2: New requirements. BSM=Beyond the Standard Model, LBLO=Long Baseline Oscillations, BNB=(FNAL) Booster Neutrino Beam, MI=(FNAL) Main Injector, LE=Low Energy, HE=High Energy, NSI=Non Standard Neutrino Interactions. Table from NF.

Accelerator	Energy [GeV]	article	Power [MW]	Timing (Pulse length, repetition rate, RF frequency)	Type	comments
BNL-BLIP	0.2	H-	0.025-0.03	440 µs @ 6.67 Hz (200 MHz)	Linac	
BNL-Booster	2	p	0.03	xxx @ 6.67 Hz (xxx MHz)	RCS	
BNL-AGS (FX)	28	p	xx	Xxx @ 0.333 Hz (xxxMHz)	Synch.	
BNL-AGS (SX)	28	p	xx	O(1) s @ 0.333 Hz (debunched?)	Synch.	
CERN LINAC4	0.16	H-	0.0021	600 µs @ 0.83 Hz (352 MHz)	Linac	ep. rate could be increased with some upgrade
CERN PSB	1.4-2	p	0.02/0.026	2 µs @ 0.83 Hz (4 bunches)	hrotron. (4 rings)	
CERN PS	20	p	0.027	20 ns @ 0.83 Hz (1 bunch)	Synch.	

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:ERN SPS (FX)	400	p	0.57	µs (or 2x10.5 µs) @ 0.17 Hz (200 MHz)	Synch.	:ould be possibly increased
:ERN SPS (SX)	400	p	0.36	~1 s @ 0.14 Hz (debunched)	Synch.	
CERN LHC	7000 ivalent .04e8)	p/p	36.8	Hours @ 40 MHz	Collider	uld be the power of a fixed target n with a current corresponding to nber of interactions per second at e LHC IP (assuming a total cross on of 110 mb) and with an energy ng a centre of mass energy of 14 TeV. The luminosity considered is $2x10^{34}$ $cm^{-2}s^{-1}$.
CSNS-Phase I	1.6	H-	0.1	550 ns @ 25 Hz (2.44MHz, 2 bunches)	Linac leV)+RCS	
FNAL Linac	0.4	H-	0.012	50 µs @ 15 Hz (162.5 MHz)	Linac	
FNAL Booster	8	p	0.04	1.6 µs @ 7 Hz (52.8 MHz)	RCS	
FNAL MI	120	p	0.4	9.4 µs @ 0.45 Hz (53.1 MHz)	Synch.	
J-PARC linac	0.4	H-	0.33	0.5 ms@25 Hz (**324/972** MHz)	Linac	

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J-PARC RCS	3	p	0.8	1 μs @ 25 Hz (2 bunches)	RCS	
-PARC MR (FX)	30	p	0.52	5 μs @ 0.4 Hz (8 bunches)	Synch	
PARC MR (SX)	30	p	0.05	2 s @ 0.19 Hz (debunched)	Synch	
.ANSCE area A	0.8	H-	0.8?	625 μs @ 120 Hz (xxxMHz)	Linac	sently operates at ~100 kW
ANSCE isotope production line	0.1	p	0.25	625 μs @ 40 Hz (xxxMHz)	Linac	
ISIS	0.8	H-	0.2	0.5 μs @ 40 Hz to TS1 (xxx MHz) 0.5 μs @ 10 Hz to TS2 (xxx MHz)	ıac + RCS	kW to TS-1, 40 kW to TS-2
PSI	0.59	p	1.4	CW (50 MHz)	Cyclotron	
SNS	1	p	1.4	700 ns @ 60 Hz (1 MHz)	-accumulator	

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TRIUMF	0.52	p	0.1	CW (23 MHz)	Cyclotron	

Table 3: Present capabilities (TS=Target Station, RCS=Rapid Cycling Synchrotron, MR=Main ring, FX=Fast extraction, SX=Slow Extraction, h = harmonic number). Power is quoted for exclusive operation in a certain mode. The frequency refers to the main bunch repetition frequency. The beam power quoted for the LHC is the power of a fixed target beam with a current corresponding to the number of interactions per second at one LHC IP and having an energy giving a center of mass energy of 14 TeV

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Accelerator	Kin. Energy [GeV]	particle	Power [MW]	Timing	Type	Comments/Timescale
BNL BLIP	200	H-	50-60	880 µs @ 6.67 Hz (200 MHz)	Linac	Timescale?
BNL BLIP - BLAIRR	>1	H-	0.25-0.3	880 µs @ 6.67 Hz (200 MHz)	Linac	Timescale?
CSNS-Phase II	1.6	H-	0.5+	550 ns @ 25 Hz (2.44 MHz, h=2)	Linac (300 MeV)+RCS	End of 2028

ESS	2 *2.5*	P *H-/p*	5 *10*	2.86 ms @ 14 Hz (352 MHz) *2.86 ms @ 28 Hz (352 MHz) with compressor ring to compress to 1.3 ms*	Linac	2023 (projected user operation) /Potential compressor ring upgrade for neutrino physics (parameters in italics)
FNAL PIP-II LINAC	0.8	H-	0.017	540 µs @ 20 Hz (650 MHz)	Linac	2024
FNAL PIP-II Booster	8	p	0.166	1.6 µs @ 20 Hz (52.8 MHz)	Linac+RCS	2024
FNAL PIP-II MI	120	p	1.2	9.4 µs @ 0.83 Hz (h=53.1 MHz)	Linac+RCS+Sync h.	2024
IsoDAR	0.06 GeV/u	H2+	0.6	CW (**xxx** MHz)	Cyclotron	Timescale?
Daeδalus	0.8 GeV/u	H2+	3 stations (1+2+5) MW	1 ms x 200 Hz(relatively Arbitrary, 20% Duty Factor, ontime>=1 ms) (**xxx** MHz)	Cyclotron (IdoDAR injector)	5 emA peak current (10 mA peak protons on target). Timescale?

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HL-LHC	7000 (equivalent FT = 1.04e8)	p/p	92	Hours @ 40 MHz	Collider	2029. See comment for LHC. The luminosity considered here is $5x10^{34}cm^{-2}s^{-1}$.
ISIS	0.8	H-	0.4	0.5 μs @ 45 Hz to TS1 0.5 μs @ 5 Hz to TS2	Linac + RCS	360 kW to TS-1, 40 kW to TS-2, 30 MeV/c μ from graphite target in proton beam line to TS-1. / Timescale?
J-PARC RCS	3	p	1	1 μs @ 25 Hz (2 bunches)	RCS	2024 JFY
J-PARC MR (FX)	30	p	1.3	5 μs @ 0.86 Hz (8 bunches)	Synch	2028 JFY
SNS / PPU upgrade	1.3	p	2.8	700 ns @ 60 Hz	Linac+accumulator	Energy increased 30%, current increased 50%, 2024

Table 4 Planned upgrades and facilities

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White papers summary

A number of white papers were contributed to this working group and we include a summary of their content here.

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. In particular, the highest energy neutrino beams from an artificial source emerge from each of the collision points. The proposed Forward Physics Facility (FPF), to be located approximately 600 m from the ATLAS along the beam collision axis and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). The facility could operate parasitically to the high luminosity experiments without requiring any modification to the LHC machine or its mode of operation. The considered beam and machine parameters are those expected for the LHC after its High Luminosity Upgrade [FPF]

The LHC Injector complex has undergone a major upgrade in view of delivering the beams with the high brightness (an increase of the bunch population by a factor 2 and a reduction of the emittance by almost 50% with respect to the nominal values are expected) required for the High Luminosity LHC. The main modifications include:

- A new 160 MeV H- linac replacing the 50 MeV proton linac and a new charge exchange injection in the PS Booster
- Increased extraction kinetic energy (from 1.4 to 2 GeV) from the PS Booster to the PS
- New injection system to cope with the higher injection energy in the PS together with a reduction of the longitudinal impedance of the main RF system and a new longitudinal feedback system
- Impedance reduction and RF power upgrade for the SPS

One year after the completion of the upgrade work and the recommissioning phase the injector chain is on track (and even ahead of schedule) for demonstrating the expected beam parameters for the LHC beams. The HW upgrades are expected to benefit also the performance of the accelerators for the production of the high intensity beams serving a wide range of fixed target experiments (e.g. in the ISOLDE, Neutron Time of Flight, PS East Area and SPS North Areas). Simulation and experimental studies have started and have already allowed to increase the intensity of some of the fixed target beams while maintaining low level of beam losses, some more are planned to explore further the intensity reach of the accelerator chain. Future proposals for neutrino physics, hidden sector searches, rare kaon decays, lepton flavour violation searches could benefit of these intensity increase [CERNAcc].

New experimental proposals require high intensity beams for “monitored” neutrino beams in which the neutrino flavour and energy is tagged. In addition to a high proton intensity low-noise slow extraction is required to minimize pile-up and therefore reconstruction inefficiency. New techniques to generate pulsed slow-extracted beams have been also proposed to boost the neutrino flux with the help of magnetic horns pulsed at regular intervals and in coincidence with

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the extraction bursts or to provide a time structure employed at the neutrino detector to reduce cosmic-induced background [NUBET, NUTAG].

A high intensity, intermediate energy (O(GeV)) linac coupled with an accumulator ring to compress the long linac pulse are proposed as multi-MW proton drivers for neutrino experiments for the measurement of d_{CP} at the second neutrino oscillation peak and/or for feeding muon storage rings for neutrino physics or as test-stand for future muon colliders. A conceptual study for the upgrade of the ESS 2 GeV proton linac under construction at Lund (Sweden) has been performed. This would require an energy increase of the linac from 2 to 2.5 GeV, a new H-source with currents exceeding 60 mA and associated front-end acceleration stage, doubling the repetition rate of the linac from 14 to 28 Hz, an accumulator ring compressing the linac pulse from 0.8 ms to 1.2 ms. Particularly challenging are the charge exchange injection system that could benefit of possible development of laser stripping, beam loss control possibly requiring a collimation system in the accumulator ring, and the target station consisting of four high power targets in the present design each of them surrounded by a pulsed magnetic horn [ESS]

The case for a Neutrino Factory (NF) [NF] was presented, namely it provides uniques capabilities that compliment ongoing superbeam experiments and provides new physics, and it could be used to follow-up any observed anomalies. The NF compliments a muon factory, and shares the proton driver. The accelerator needs include muon production (multi-GeV/multi-MW p-driver, target muon source), capture (decay channel + bunch + phase rotate) and cooling (6-D cooling of muon beams + muon storage ring) and are all challenges. A recirculation linac (15 GeV) + decay ring is proposed.

The IsoDar community [Isodar] provided a comprehensive ;ist of references on work since the last Snowmass. Isodar is proposed to be built near a South Korean detector (associated with the underground mine/lab Yemilab).

A paper on synergies with non-proliferation efforts [Arms] recognizes the synergy possibilities for neutrino detector development between HEP and NNSA (non-proliferation applications). Detector technology overlaps, but nothing to do with directly with accelerators.

A summary of a workshop on cyclotrons and Fixed Field Accelerators [Cyclotron_FAA] was prepared. Cyclotron PIC simulation efforts have improved, and identified optimizations of field, RF cavity shapes, and collimation proposals provide clean beams. Studies of low energy (60 MeV) H2+ accelerators identified clean beams with sufficiently low populations of vibrational excited states from the source. Also a concept for a single stage 1 GeV cyclotron using H2+, and use of a magnetic inflector for injection were presented. Previously identified concepts such as vertical extension FFA and RFQ injection are still on going. Some conceptual developments in the past years on injection (RFQ, inflectors), improved acceleration (optimizations of field, RF cavity shapes, collimation), and improved extraction (new stripping schemes). Improvements in PIC modeling capabilities. In general, the higher energy concepts are supported by simulations, but need some experimental demonstration at least an intermediate range of design parameters.

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R&D areas [AF2TownHall10122020]:

The experimental proposals for neutrino physics, as well as the searches for the Hidden Sector and the study of rare decays all require high intensity beams and pose several challenges in the design of accelerators and their components.

Minimization of beam losses is critical to minimize damage to components and allow maintenance in case of failure keeping downtime and radiation doses to personnel as low as possible. This requires the understanding of loss mechanisms (e.g. space charge effects and halo generation mechanisms) and the implementation of these effects in simulation codes with the aim of providing a realistic model of the evolution of the beam observables (intensity, profile, etc.) profiting of the progress in High Performance Computing and algorithms. As an example, the modellization of diffusion processes is critical for the design of efficient collimation systems to protect the accelerator from uncontrolled losses. The simulation effort should be accompanied by developments of advanced diagnostics with high dynamic range to accurately characterize the beam properties (e.g. beam transverse and longitudinal distribution and in particular beam halo) to benchmark simulations and for protection and tuning purposes.

Present and future high intensity circular machines demand for H- low energy front-ends to maximize the beam brightness and minimize losses (e.g. ESSnuSB,….). High intensity H- sources are required and understanding and simulation of the H- formation process and beam dynamics at very low energy to optimize the source extraction and low-energy beam transfer to the first accelerating element (typically RFQs) are critical. This domain could profit of the synergy with similar developments required for thermonuclear fusion (e.g. ITER). In addition, reliability issues might be encountered for the stripping foils normally used for the charge exchange injection process when operating at very high intensities. Significant progress has been made in the design of alternative laser stripping schemes [SNS] but so far no operating high intensity machine **(correct?)** is using routinely laser stripping for charge exchange injection and further research and development should be pursued.

Handling multi-megawatt beams as those proposed for future neutrino beams or for the proton drivers for future muon colliders demand for extremely robust targets able to stand enormous thermal and mechanical stresses ideally over long periods and with minimum maintenance. This requires significant research and development in the choice of the materials and the engineering design and demand a careful study of failure and maintenance/repair/replacement scenarios. The latter can greatly benefit of the progress of robotics and should be considered early in the conception phase to guarantee low down time during operation and safe and affordable disposal of the irradiated material at the end of the lifetime of a project. Similar considerations apply for beam dumps and for the target of the so-called beam dump experiments where the targets and their shielding are supposed to contain a significant fraction of the hadronic cascade, though at lower beam power.

Future neutrino experiments could benefit of tagged neutrino beams [ENUBET][NuTAG] generated by the decay of momentum selected pion or kaon decays and for which the flavour, helicity and energy of each tagged neutrino is determined by accurately measuring the properties of charged particles generated in the decays producing the neutrinos. Although relying on state-of-the-art tracking devices required for the High Luminosity LHC Detector upgrades capable of operating at high particle fluxes, slow proton beam extraction (over time scales of few seconds) are required to minimize pile-up. For the same reason the ripple of the extracted beam intensity needs to be minimized. The refinement of extraction techniques aiming at reducing the sensitivity

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to unavoidable noise (e.g. those coming from the mains) is important and could benefit other accelerator applications (e.g. medical applications like hadron therapy).

Given the high beam power, maximization of the efficiency of future accelerators is mandatory to guarantee the sustainability and affordability of the research conducted with these machines in view of reducing the carbon footprint and contain the operation costs, particularly in the present international context of increasing energy prizes. Development of efficient energy storage concepts for pulsed accelerators, high efficiency RF sources, superconducting solutions for accelerating cavities and magnet, recovery of waste heat are just a few possible examples of the areas of research to be strengthened.

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